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Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor
Building and Fire Research Laboratory

September 2002

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

ABSTRACT

The National Institute of Standards and Technology's Building and Fire Research Laboratory, as the national laboratory responsible for research into building fires, initiated a program prior to the events of September 11 to put structural fire protection on a stronger scientific footing. The first phase of this program focused on addressing the poor performance of high strength concrete (HSC) in fire, which was not yet reflected in any design codes. The catastrophic collapses of the World Trade Center underscored the need not only to accelerate but also to broaden this effort to include fire safety design of steel construction. A workshop calling upon scientific and engineering experts in materials, fire protection, and structural design was held February 19 and 20, 2002, at NIST to identify the research required to underpin meaningful test and predictive methods for use in evaluating the performance of structures subject to real fires. The specific objectives of the workshop were to review current practices for achieving fire resistance; to explore the promise of fire dynamics simulations and structural behavior predictions at elevated temperatures; to identify new fire resistance options coming from materials science; to identify opportunities and needs in advanced computational methods; and to identify applications and needs for emerging measurement, instrumentation and test methods. Commercial, academic and government experts provided background and suggestions on how best to achieve the objectives, from the perspective of the discipline they represented. This information is summarized in these Proceedings. Key recommendations include the following:

- to develop new experimental methods for measuring high temperature thermal and mechanical properties of structural and insulating materials;
- to develop experimental facilities and capabilities for measuring the behavior of real-scale connections and assemblies under controlled fires that permit extrapolation to total building frame behavior up to the point of failure;
- to improve the physics and speed of sophisticated numerical models, and to expand the use and acceptance of proven, simpler computational design tools;
- to establish as a goal the need to predict the performance of coupled building systems in elevated temperatures to the point of impending failure;
- to develop a strategy to effectively incorporate technological advances in structural fire resistance into engineering tools that support performance-based design alternatives;
- to train and improve communications between the architecture and engineering professions; and
- to appreciate the needs of, and better train, building code officials and regulators.

ACKNOWLEDGEMENTS

The success of any workshop is dependent upon the hard work of the individual speakers and facilitators, and the efforts of participants motivated toward a common goal. These proceedings are an assimilation of the contributions from the workshop participants, with some of the text coming directly from the presentations of the invited panelists from the following organizations:

Arup Fire, UK (Barbara Lane)
Hughes Associates (Craig Beyler and Philip DiNenno)
Institute for Research in Construction, NRC-CANADA (Venkatesh Kodur)
Lehigh University (James Ricles)
National Institute of Standards and Technology (Howard Baum, Shyam Sunder,
  William Pitts, John Gross, Edward Garboczi, and William Grosshandler)
University of California, Berkeley (Brady Williamson, Abolhassan Astaneh)
University of Edinburgh (Asif Usmani)
University of Liege (Jean-Marc Franssen)
University of Maryland (James Milke and Fred Mowrer)
University of Utah (Adel Sarofim and Philip Smith)
SP Fire Technology (Ulf Wickstrom)
Stanford University (Greg Deierlein)
Wiss, Janney, Elstner Associates (Robert H. Iding)

Verbatim copies of the presentations are included in the appendix. In addition, the editor wishes to acknowledge the assistance of Ms. Wanda Duffin of NIST, who helped with the planning, organizing and running of the workshop.

TABLE OF CONTENTS

FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION RESEARCH NEEDS

BACKGROUND

The enormity of the loss of life and the economic impact caused by the destruction on September 11, 2001, has led the scientific and engineering community to recognize its responsibility to understand the technical issues associated with the buildings that collapsed that day. The Twin Towers, as designed, withstood the physical impact of the aircraft but succumbed to the thermal impact of the ensuing fire. WTC 7, with unknown but significantly less structural damage collapsed hours later, apparently due to the fire that burned unchecked, making it the first instance of a building of such a design to ever fail by this method. The relative amount of damage to the Pentagon due to the initial impact and due to the subsequent fire has been investigated, which is important if we are to learn the right lessons from the observed building performance, occupant behavior, and fire fighter response.

Central to all these events is the fire resistance of the structures. No one did a calculation ahead of time to predict how resistant to heat these buildings were in the event of an extreme fire. Why? Consider the following reasons:

- There was no code requirement to include a realistic fire scenario.
- A plane crash into a high-rise building followed by severe fire had never occurred.
- Structural engineers anticipated a possible accidental hit by an aircraft, but the architect responsible for fireproofing did no fire analysis.
- The structural elements were protected with fire resistant coatings and panels following the accepted practice of the day.
- In the late 1960s (when the buildings were designed), the engineering tools available to predict the performance of structural connections and assemblies in an actual large fire setting were primitive.
- The prevailing mindset at the time the Towers were designed was "the engineer designs the structure and the architect specifies the fire protection."

The National Institute of Standards and Technology's (NIST's) Building and Fire Research Laboratory (BFRL), as the national laboratory responsible for research into building fires, initiated a program prior to the events of September 11 to put structural fire protection on a stronger scientific footing. The first phase of this program focused on addressing the poor performance of high strength concrete (HSC) in fire, which was not yet reflected in any design codes. As a result, scientific data and knowledge related to mechanical properties of HSC at high temperature, methods for mitigating explosive spalling in fire-exposed HSC, and recommended code provisions for HSC strength-temperature relationship were developed and published [30-32]. However, the catastrophic collapses of the World Trade Center underscored the need not only to accelerate but also to broaden this effort to include fire safety design of steel construction. A workshop calling upon scientific and engineering experts in materials, fire protection, and structural dynamics was held February 19 and 20, 2002, at NIST in Gaithersburg, MD, to identify the fundamental research required to underpin meaningful test and predictive methods for use in evaluating the performance of structures subject to actual fires. The agenda with the topics covered, speakers names and affiliations is shown in Appendix I. Appendix II includes a list of those who attended, and Appendix III contains the presentations.

WORKSHOP ORGANIZATION AND OBJECTIVES

The tone of the workshop was set by Sunder (see Appendix III. A) who provided an overview of the NIST strategy for advancing standards, technology and practices leading to cost-effective safety and security of buildings and critical facilities, with explicit reference to the proposed investigation of the World Trade Center disaster. In addition to the 24 month investigation, the strategy calls for sustained research and a developmental effort in structural fire protection; human behavior, emergency response and mobility; building vulnerability reduction; and an industry-led roadmap for construction and infrastructure support. As part of the structural fire protection program, research and development are proposed for methods of fire resistance determination, improved fire resistance coatings and materials, fire safety design and retrofit of structures, and mitigation of progressive collapse.

Grosshandler laid out a vision that extended beyond a direct response to the events of 9/11/01 (see Appendix III. B): ***Vision*** *Scientifically-based performance predictions for the design and operation of buildings, accepted by regulators and major stakeholders, that enable a rational balance of competing demands for fire safety, function, economy, aesthetics, and environmental stewardship.*

Improvements to current understanding of instrumentation development, computational methods, and measurement techniques are needed to achieve this vision. The need for performance prediction extends to building materials, products, structural elements, and systems up to the point of imminent fire-caused collapse of a significant load-bearing element. Assessment of the uncertainties in the prediction of performance, and convincing the regulators and stakeholders of the validity of the uncertainty established, will be as important as the development of the tools themselves.

The specific objectives of the workshop were laid down by Grosshandler as follows:

- to review current understanding of practices for achieving fire resistance;
- to explore the promise of fire dynamics simulations and structural behavior predictions;
- to identify new fire resistance options coming from materials science;
- to identify opportunities and needs in advanced computational methods; and
- to identify applications and needs for emerging measurement, instrumentation, test methods.

Commercial, academic and government experts provided background and suggestions on how best to achieve the workshop objectives, from the perspective of the discipline they represented. This information is summarized in the following sections, loosely categorized as History and Current Practice, Fire Testing and Simulations, Fire Resistant Materials, and Structural Performance. The final sections provide a summary of the workshop and list specific recommendations.

APPENDIX I. Workshop Agenda

RESEARCH NEEDS FOR FIRE RESISTANCE DETERMINATION & PERFORMANCE PREDICTION

National Institute of Standards and Technology
Gaithersburg, Maryland, USA
Building 101, Lecture Room B
February 19 and 20, 2002

WORKSHOP AGENDA

Tuesday

8:45 Introductory Session (Chair: **William Grosshandler**, Chief, Fire Research Division, NIST)

Welcome to NIST, **Jack Snell**, Director, Building and Fire Research Laboratory

NIST Response to Sept. 11, **Shyam Sunder**, Chief, Structures Division, NIST

Goals of Workshop, **William Grosshandler**

9:20 Session I (Chair: **William Grosshandler**)

Overview of Designing Buildings for Fire Resistance, **Craig Beyler** and **Philip DiNenno,** Hughes Associates, Baltimore, USA

ASCE/SFPE Standard on Performance-based Structural Fire Protection Analyses, **James Milke**, Department of Fire Protection Engineering, University of Maryland, USA

10:00 Break

10:20 Session II (Chair: **William Pitts**, Fire Research Division, NIST)

Simulation of Accidental Fires and Explosion, **Adel Sarofim** and **Philip Smith**, Department of Chemical Engineering, University of Utah, USA

Research Needs for Building Fire Models, **Howard Baum**, Fire Research Division, NIST, USA

Simulation of the Cardington Fire Tests, **Asif Usmani,** University of Edinburgh, UK

Fire Resistance Evaluation of Large-scale Structural Systems, **Venkatesh Kodur**, Institute for Research in Construction, NRC-CANADA

Improved Fire Testing in Combination with Calculation, **Ulf Wickstrom**, SP Fire Technology, Borås, SWEDEN

Discussion and short presentations from participants on fire modeling

12:20 Lunch, NIST cafeteria

1:15 Session III (Chair: **Edward Garboczi**, Building Materials Division, NIST)

Degradation in Performance of Installed Fire Resistance Materials, **Frederick Mowrer**, Department of Fire Protection Engineering, University of Maryland, USA

Performance-Based Analytical Prediction of Fireproofing Requirements in Complex Buildings, **Robert H. Iding**, Wiss, Janney, Elstner Associates, San Francisco, USA

Materials for the Fire Protection of Structural Steel, **Brady Williamson**, Department of Civil and Environmental Engineering, University of California, Berkeley, USA

Protection of Steel Structures Against Blast, Impact and Ensuing Fires, **Abolhassan Astaneh**, Department of Civil and Environmental Engineering, University of California, Berkeley, USA

Discussion and short presentations from participants on fire resistant materials

3:20 Session IV (Chair: **John Gross**, Structures Division, NIST)

Structural Fire Modeling: Where is the Frontier Nowadays? **Jean-Marc Franssen**, Institute de Mécanique et Génie Civil, University of Liege, BELGIUM

Fire Resistance and Performance Prediction: Structural Analysis Issues and Research Needs, **James Ricles**, Department of Civil and Environmental Engineering, Lehigh University, USA

Parallels Between Performance-Based Engineering for Fire and Earthquake Hazards, **Greg Deierlein**, Department of Civil and Environmental Engineering, Stanford University, USA

A Consultant's Wish List for a Numerical Model of Structural Response to Fire Conditions, **Barbara Lane**, Arup Fire, London, UK

Discussion and short presentations from participants on structural modeling

5:00 Break-out sessions to identify research needs (**W. Pitts** [LR-B], **J. Gross** [B111], and **E. Garboczi** [B113], facilitators)

6:30 Dinner and informal discussion at local restaurant

Wednesday

8:30 Reconvene breakout sessions (**W. Pitts** [LR-D], **J. Gross** [B111], and **E. Garboczi** [B113])

10:45 Summary of breakout session discussions (spokespersons from parallel sessions), LR-D

12:15 Lunch, NIST cafeteria

1:15 Open discussion, LR-D (Chair: **W. Grosshandler**)
Workshop Recommendations and Assignments

4:00 Adjourn

APPENDIX II. Workshop Attendance List

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R. Summary of Red Breakout Session

Priority List

- Communication between disciplines/AHJ etc
- Catalogue of design fires
  - Data from full-scale validation fires
- Review of predictive tools
  - fire, structural, material models
- Test methods and database of material properties at elevated temperatures
  - fire resistive materials and structural materials
- Assemble steering committee - performance, economic benefits
- Assemble themed development teams
- Model for structural response to fire
- Transfer responsibility for fire proofing from architect to FPE/PEs

Limitations/research needed

- <u>Communication between disciplines NEW ITEM</u>
  - fulltime positions at NIST
  - educating younger designers etc
  - Info to AHJ, structural engineers etc
  - publishing now and future work
  - development team - fire modelers, structural engineers, computer scientists and material scientists
  - steering committee to define goals and objectives
- <u>Materials</u>
  - Clarify what we know
  - set of thermal/physical properties
  - standardized tests to achieve these
  - Information on durability and reliability
  - What maintenance is needed to achieve a given level of reliability
  - Impact of materials on fire safe environment
  - understand technical basis behind current prescriptive requirements
  - Need total evaluation system
  - concrete NB

Limitations/research needed

- <u>Installation</u>
  - assess effects of material variability on installed performance
- <u>Test methods</u>
  - lack of understanding of science underlying existing methods and use of data derived
  - Extrapolations of single element test to complex assemblies
  - Many current test methods not well suited to collecting useful data
  - new fire tests addressing the gaps
  - using existing tests and current data essential

Limitations/research needs

- <u>Predictive tools</u>
  - over reliance on empirical data, lack of scientific basis
  - integration of gas phase models with structural models
  - state of the art review and summary of existing tools
  - develop public sector models for prediction of material properties
  - full scale fully instrumented validation tests with interaction between modellers and experimentalists

Research needs

- <u>Predictive tools</u>
  - Review fluid/structure interaction models within AND outside fire community
  - Define a design fire
  - Develop first stage prototype simulation methodology joining a selected specific choice of existing software for:
    - fire simulation
    - thermal/mechanical properties
    - structural response
    - incl. validation and performance ideas
  - need practical predictive tools for progressive collapse in fire (based on existing models?)
  - extend capabilities of current CFD models to better address flashover conditions

Limitations/research needs

- <u>Maintenance and Inspection</u>
  - formal inspection and maintenance procedure for passive fire protection systems - prior to occupancy and throughout service life
  - explore potential for smart buildings
  - need information on time dependent degradation of passive systems


Funding/collaboration
Primary need for Government funding
results need to be public not favor a particular industry/business
Sweat equity from business/industry through Prof/trade
Lobbying congress
Associations
Architects
AHJ
Insurance groups1
Europeans but US must take the lead
FEMA, Fire Service
ASCE,AISC, ASME, SFPE,Trade groups, AIA

S. Summary of Blue Breakout Session

End Products

- Validated Engineering Tools
- Design Framework for new construction
- Design for retrofitting existing construction
- Integration of structural and fire: performance based design
- Education of engineers, designers, AHJs (Make them work together)

Predictive/Design Tools

- Fire Growth – we could use approaches such as
  - Stick with specified, space independent model
  - Use simplified approach (including space/opening effects)
  - CFD Model
    - Can't be used for direct routine design but can be used to develop design tools and for special design issues
- Bottom line, need to establish and define need based approach

Uncertainty/Reliability

- How much uncertainty is acceptable, i.e. sensitivity of response to the uncertainty
  - Depends on objective
- Development of a standardized process for uncertainty quantification and analysis techniques
- Integration of fire mitigation strategies

Predictive Tools, cont.

- Heating of the Structure – Insulating and fire proofing materials
  - Need to be able to demonstrate stickability (mechanical performance)
  - Need information to determine destructive decomposition (mechanical and thermal) of materials such as mineral wool and fiberglass
  - Need thermal properties as a function of temperature and temperature rise
  - Need answer to importance and role of geometric issues (containment issues)

Predictive Tools, cont.

- Heating of the Structure – Structural Materials
  - Thermal/mechanical properties as a function of temperature and temperature rise
    - Steel: A36 and similar (what are similar, for example HSLA) – creep at very high temperature
    - Special steel (light gage steel, high strength/performance steels, welds, bolts, rebar, pre-stressing) – all properties
    - High Strength Concrete –
    - Normal Strength Concrete –
    - FRPs, Aluminum, timber, glass etc – all properties

Predictive Tools, cont.

- Validation of existing structural response tools for assemblies (including connections) and systems under fire conditions (including soot and other fire phenomena effects)
- Development and validation of structural response engineering sub-models for specific fire phenomena
- Fire barrier analysis and design

Predictive Tools

- Structural Response
  - Need incorporation of high strength concrete behavior in analysis and design
  - Need knowledge to develop a simplified model; this then needs to be validated
  - Need to know how to apply the "fire load" as a load combination to the entire structure.
  - Need to define design limit states (i.e. objectives of design)

Other Objectives

- Develop performance criteria for insulating materials
  - In service issues including impact
  - Maintenance and inspection over the life of the structure
- Develop performance criteria for structural materials, products and systems

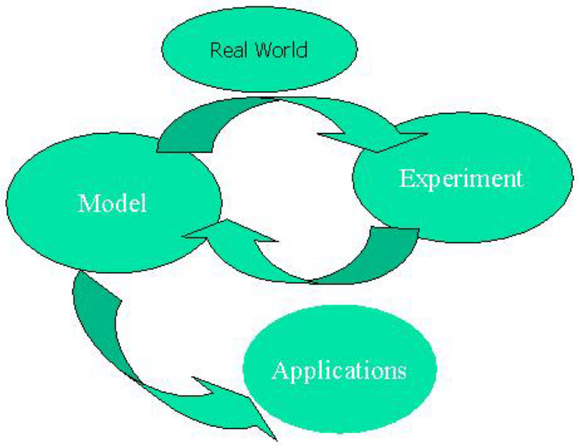
Experimental Studies

- Establish methods for validation
- Develop improved fire measurement technologies, esp. heat transfer
- Evaluate use of existing ASTM standard for fire model validation
- Develop standardized test methods for material property determination
- Develop standardized test methods for structural components such as connections.

Validation

- Round Robin testing of models and experiments including material measurements

T. Summary of Green Breakout Session



Needs

- Fire exposure
- Thermal response
- Structural response
- Mitigation strategies
  - Redundancy
  - Prevention
    - Design with fire safety in mind
- Communications
  - Engineers
  - Consultants
  - Regulators

Fire exposure

- Instrumentation of real fires to obtain better
  - Fuel load characterization
    - Impact of spatial distribution
  - temperature/oxygen histories
  - Heat flux
  - Products of combustion
  - Full cycle (heating and cooling) data
- Model behavior of non-structural elements

Thermal response

- Material properties, particularly of slabs
  - Data base of existing properties
- Dehydration and cracking need to be understood
- Impact of fireproofing materials
- Improved high temperature performance/data
  - Modification of HSC (polymer inclusion)
  - Composite
- Hysteresis (Short-Hot vs Long-Cool)

Structural response

- Deflections and stresses
- Connections
- Fire proofing materials
- Heating and cooling cycles
- Coupling fire and structural models
  - Zone with frame models

Multiple level of models

Couple models with experiments
    validation of models
    design of experiments/measurements
Models of fundamental properties
    Computational chemistry, molecular dynamics, crack development
Models of pyrolyis behavior
    Impact of exposure history
    Product distribution: heating content, environmental impact
Models of behavior under prescribed temperature/oxygen histories
Zone models
Need to model non-loading (glazing) as well as load-bearing
Detailed CFD/Finites element models

Validation/Measurements

- Fundamental properties
  - Particularly **effect of temperature**
  - Constitutive properties of slabs (concrete)
- Single step experiments
  - Ignition, Firespread
- Multiple step experiments
  - Corner fires
  - Flash over
- Integrated tests
  - Enclosure tests
  - Building fires
    - Proper instrumentation to capture spatial and temporal aspect of fires
    - Non-structural components, e.g., glazing behavior
    - Local stresses and deflection
    - Heat transfer through connections
- Real world
  - Characterize real word buildings from a fire perspective
  - Document data from accidental fires

Performance Objectives

- Performance prediction
  - Test conditions versus real world
  - Temperature time curves
    - Real world has dimensionality, which has important implication that determines the response
      - e.g. plume impacting on the ceiling has not deconvoluted convection and radiation; problems of flash over; impact of air availability
    - Need to translate test results into real world situations
      - Integrity of fire walls major factor
      - Fire test data need to be used to validate models
      - There is need of data on more complex structures
      - Need to have data from small, to intermediate, to full scale